Appendix E
Hydraulics

Table of Contents

Appendix E
Hydraulics

Ultimately, the Aquatic Habitat Guidelines program intends to offer one complete set of appendices that apply to all guidelines in the series. Until then, readers should be aware that the appendices in this guideline may be revised and expanded over time.

Within the context of streambank protection, hydraulics refers to the laws governing the movement of water within a channel and the forces generated by this movement. Hydraulic effects result in the erosion of channel banks and scour of the channel bed. This appendix describes how to calculate shear stress (erosional forces along a bank or bed) and scour depth in natural stream channels. Refer to Chapter 2, *Site Assessment* for descriptions of these hydraulic parameters and their relationship with geomorphic processes and aquatic habitat.

SHEAR STRESS

Shear stress is an important parameter in streambank-protection design. All materials used for streambank restoration and protection, whether manufactured or natural, must be able to withstand the expected shear stress, or the bank will continue to be prone to failure. Thus, in streambank-protection design, all materials and vegetation types must be chosen based on the expected shear for a given design flow (for example, the 50-year discharge) at their point of installation. Shear stress is typically measured in units of pounds per square foot (psf).

The material and vegetation types required to resist erosion may vary with location. *Figure E-1*[1] shows the theoretical distribution of shear stress on stream beds and banks on a straight section of trapezoidal channel. Based on the diagram, materials and plants capable of withstanding greater shear forces are required lower on the bank, while a lighter-duty treatment may be sufficient near the top of the bank. When designing vegetated streambanks that include temporary surface protection, such as biodegradable fabric, the designer must be sure that the shear resistance of both the temporary protection (e.g., coir fabric) and the long-term surface treatment (vegetation) are adequate to withstand hydraulic forces at that location. In addition, when making use of vegetation as the primary erosion protection, factors such as species, site aspect, shade, soil type, moisture conditions and local climate must all be considered.

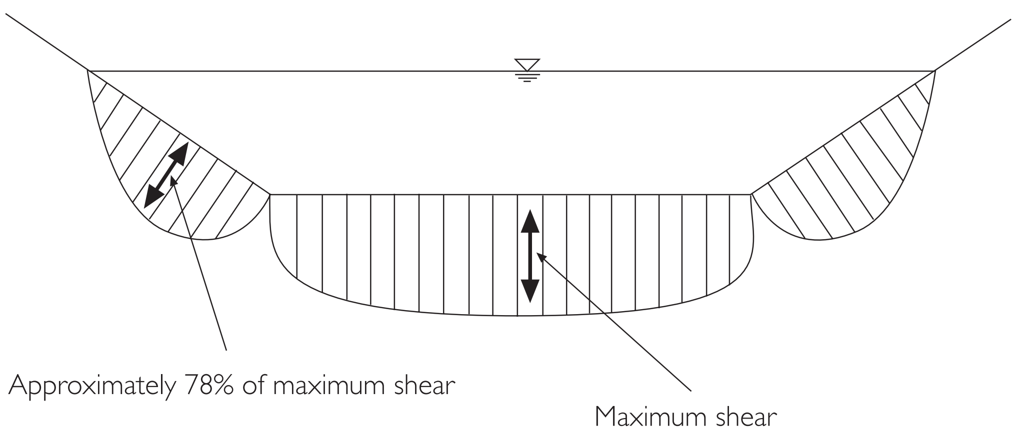

Figure E-1. Typical shear stress distribution in a channel.

Typical levels of tolerated shear stress for various erosion-control materials are shown in *Table E-1*. There is no standardized testing procedure that accounts for the effects of weather, repetitive inundation and long-duration inundation. Therefore, the values in *Table E-1* should be applied using professional judgment, and they should take into account variables unique to the project location.

Erosion-Control Materials	**Tolerated Shear Stress (psf)**
Straw with net	1.4
Coir mats and fabrics	Approx. 1-3 (varies by product)
Synthetic mats	Approx. 2-8 (varies by product)
Class A vegetation: Weeping lovegrass — excellent stand, average height 30" Yellow Bluestem Ischaemum — excellent stand, average height 36"	3.7
Class B vegetation: Kudzu — dense or very dense growth, uncut Bermuda grass — good stand, average height 12" Native grass mix (long and short midwest grasses) — good stand, unmowed Weeping lovegrass — good stand, average height 13" Lespedeza sericea — good stand, not woody, average height 19" Alfalfa — good stand, uncut, average height 11" Blue gamma — good stand, uncut, average height 13"	2.1
Class C vegetation: Crabgrass — fair stand, uncut, height 10" to 48" Bermuda grass — good stand, mowed, average height 6" Common lespedeza — good stand, uncut, average height 11" Grass-legume mix — good stand, uncut, height 6" to 8" Centipede grass — very dense cover, average height 6" Kentucky bluegrass — good stand, height 6" to 12"	1.0
Class D vegetation: Bermuda grass — good stand, cut to 2.5" height Common lespedeza — excellent stand, uncut, average height 4.5" Buffalo grass — good stand, uncut, height 3" to 6" Grass-legume mix — good stand, uncut, height 4" to 5" Lespedeza sericea — very good stand, cut to 2" height	0.6
Class E vegetation: Bermuda grass — good stand, cut to 1.5" height Bermuda grass — burned stubble	0.4
1" diameter gravel	0.3
2" diameter gravel	0.7
6" rock riprap	2.0
12" rock riprap	4.0

Table E-1. Tolerable shear stresses of various materials.[2]

ESTIMATING SHEAR STRESS

Shear equations presented in this appendix allow the designer to estimate bed and bank shear in straight stream reaches and bends. In addition, a means of estimating bank shear as a function of height on the streambank is presented. It is important that those who use the equations presented in this appendix be familiar with hydraulic-analysis methods and the concepts of shear and scour. It is recommended that hydraulic analyses be completed by a qualified hydraulic engineer or a professional with equivalent experience.

Bed Shear Stress in a Straight Reach

According to the U.S. Department of Transportation,[2] shear stress on the stream bed in a straight reach is expressed as:

$$\tau_{bed} = \gamma S_e R_h \qquad \text{(EQUATION 1)}$$

Where: τ_{bed} = *maximum bed shear stress in lb/ft^2 (psf)*
γ = *the specific weight of water = 62.4 lbs/ft^3*
S_e = *energy slope in ft/ft (see below)*
R_h = *hydraulic radius in ft (see below)*

S_e *is the slope* of the hydraulic grade line. This slope is usually similar to the bed slope (gradient) and is occasionally replaced by bed slope in hand calculations. A standard and effective way to calculate channel slope from a surveyed profile is to base the elevation change on the elevations of the thalweg at "zero-flow points." Zero-flow points are the points in the bed that would control the pools upstream of major riffles if there were no water flowing in the channel. In a braided channel, or channels without defined riffles, the mean bed elevation should be used. The mean bed elevation should be determined from several closely spaced cross sections. The U.S. Army Corp of Engineers' hydraulic program, HEC-RAS, can output bed shear stress as well as energy slope.

R_h *is the hydraulic radius*, which is the cross-sectional area of the wetted channel (A) divided by the length of the wetted channel perimeter (P) at the design flow being considered. This value is occasionally replaced by depth of flow, y, but this should only be done when the width of the channel far exceeds the depth of the channel. As a rule of thumb, always use R_h = A/P.

Bank Shear Stress in a Straight Reach

By approximating the channel cross section as a trapezoid or rectangle, the bed shear stress can be transformed into the maximum bank shear stress. This stress acts approximately one-third of the distance up the bank (from the bed) and can be approximated by multiplying by a factor (see *Figure E-1*). For most channels, multiplying the maximum bed-shear estimate by a factor of 0.8 provides a conservative estimate of the expected maximum bank shear. This approximation applies only to a relatively straight reach of stream.

Using U. S. Department of Transportation's formula,[2] calculate maximum bank shear stress in a straight reach as follows:

$$\tau_{bank} = 0.8\, \tau_{bed} \qquad \text{(EQUATION 2)}$$

Where: τ_{bed} *= maximum bed shear stress in lb/ft^2 (psf)*

Note: the factor 0.8 can be adjusted for high width/depth ratios

Shear stress on the upper bank can be estimated using the following equation:

$$\tau_x = C\, \tau_{bank} \qquad \text{(EQUATION 3)}$$

Where: τ_x *= bank shear at distance x from stream bottom (psf)*
τ_{bank} *= maximum bank shear stress (psf)*
C *= coefficient from Table E-2*

Distance x (feet from stream bottom)**	Coefficient C
1.00y	0.00
0.90 y	0.14
0.80y	0.27
0.67 y	0.41
0.60 y	0.54
0.50 y	0.68
0.40 y	0.79
0.33 y	0.80
0.20 y*	0.70
0.10 y*	0.50
0.00 y*	0.00

Notes: * Although Lane's Diagram indicates zero shear at the base of the bank, for design purposes it is recommended that the maximum bank shear, as calculated above, be assumed to be present for the lower one-third of the bank height.
** *y = stream depth (ft)*

Table E-2. Coefficient C vs. depth.

Shear Stress in Bends

Flow around bends creates secondary currents that exert higher shear forces on the channel bed and banks than those found in straight sections. Several techniques are available for estimating shear stress in bends. A relatively simple and widely used method, presented by U. S. Department of Transportation,[2] estimates maximum shear stress on channel banks and bed occurring within bends. This equation, however, does not differentiate between bank and bed shear stress.

The maximum bed/bank shear stress is primarily focused on the bank and bed on the outside portion of the bend (*Figure E-2*). The maximum bed/bank shear stress in a bend can be calculated by:

$$\tau_{bend} = K_b \tau_{bed} \qquad \text{(EQUATION 4)}$$

Where: τ_{bend} = *maximum shear stress on bank and bed in a bend (psf)*
τ_{bed} = *maximum bed shear stress in adjacent straight reach (psf)*
K_b = *bend coefficient (dimensionless)*
$= 2.4\, e^{-0.0852(R_c/b)}$
(alternatively, K_b *can be determined from Figure E-3)*
where: R_c = *radius of curvature of bend (ft)*
b = *bottom width of channel at bend(ft)*

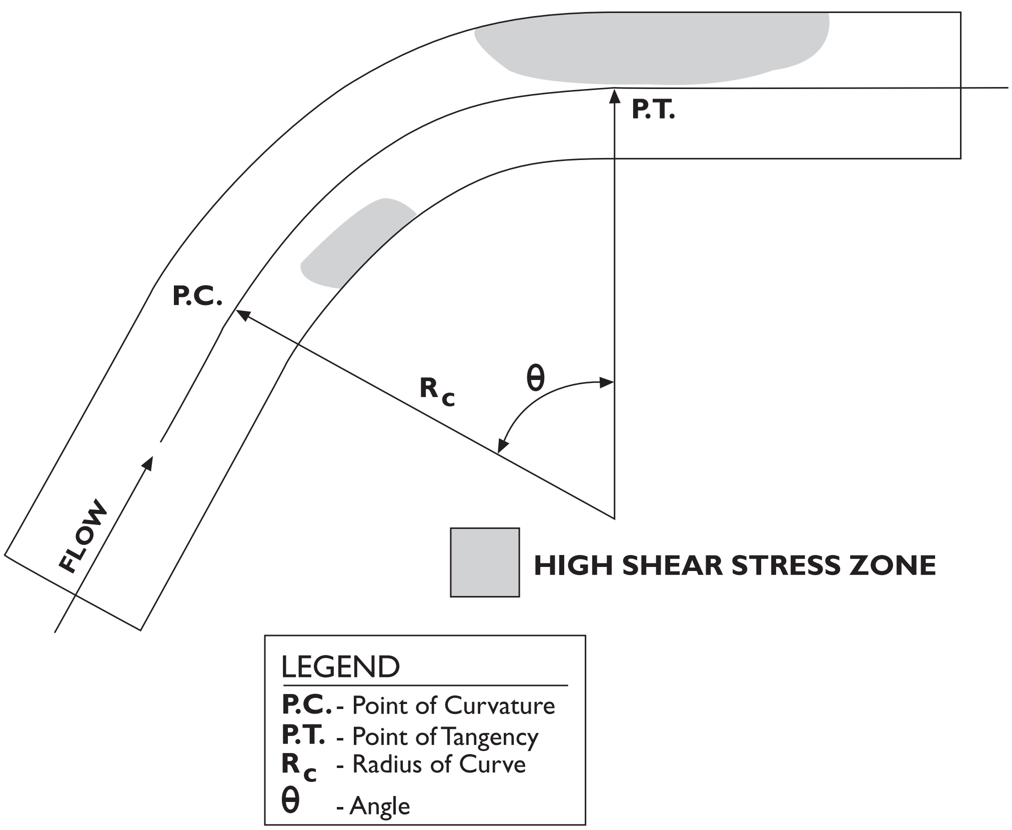

Figure E-2. Shear-stress distribution in a channel bend.

K_b	=	**Bend correction factor**
R_c	=	**Radius of curvature**
b	=	**Channel width**

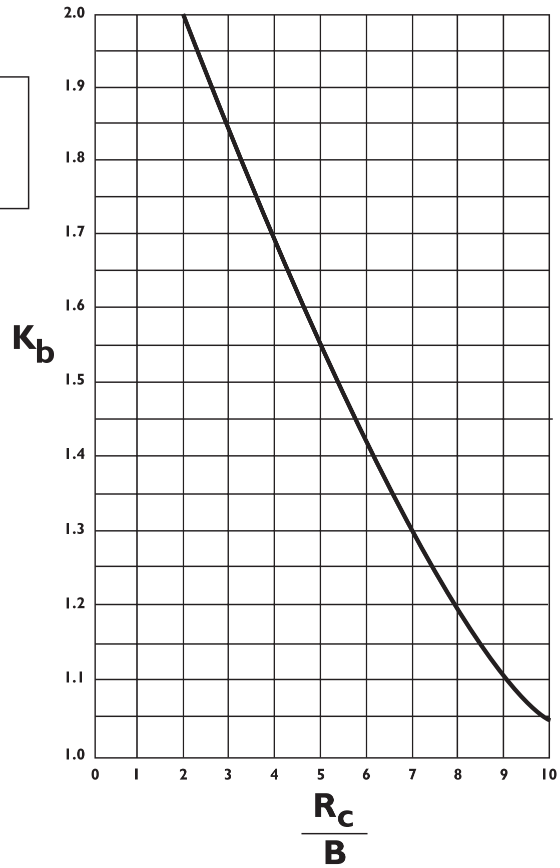

Figure E-3. Bend correction factor chart.

Analysis of the vertical distribution of shear stress on banks in bends is not well defined. Secondary currents found in bends complicate shear analysis in these regions. Equation 4 can be used as a rough estimate of shear distribution on banks in bends, but it does not account for secondary currents. It is recommended that vertical shear distribution in bends be estimated using Equation 4, with judgment based on the severity of the bend and the degree of expected super-elevation of the water surface around the bend. The water-surface elevation increases around the outside of bends as the channel banks exert centrifugal forces on the flow. This super-elevation can be estimated using the following equation[2]:

$$\Delta y = V^2 W / (g R_c) \qquad \text{(EQUATION 5)}$$

Where: Δy = *super-elevation of water surface (ft)*
V = *average velocity of flow (ft/s)*
W = *channel top width (ft)*
g = *acceleration due to gravity (32.2 ft/s²)*
R_c = *radius of curvature of bend (ft)*

SCOUR

The importance of scour in bank erosion and in the creation of fish habitat is discussed in Chapter 2. This appendix provides methods to predict the depths of scour at embankments and instream structures. Accurate prediction of scour depth is important when designing bank toes and cross-channel structures, such as drop structures and anchoring systems. In addition, the calculation of scour depth allows the designer to predict the effectiveness of instream structures intended to induce scour.

Most of the scour equations presented here were developed to predict hydraulics phenomena associated with man-made structures, such as bridges, located within relatively large, often sand-bed, streams. There are no widely used scour equations developed specifically for use on gravel-bed streams, so the equations developed for sand-bed streams are presented in this appendix along with methods of modification and interpretation that allow their application to gravel-bed streams with larger bed material.

Calculating Potential Depth of Scour

Anticipating the maximum scour depth at a site is critical to the design of a successful bank treatment. It defines the type and depth of foundation needed. Scour depth is also useful when designing anchoring systems or estimating the depths of scour pools adjacent to in-channel structures. Determining the maximum depth of scour is accomplished by:

- identifying the type(s) of scour expected (see next section, *Types of Scour*);
- calculating the depth for each type of scour;
- accounting for the cumulative effects of each type of scour (If more than one type of scour is present, the effects of the scour types are additive); and
- reviewing the calculated scour depth for accuracy based on experience from similar streams, conditions noted during the field visit and an understanding of the calculations.

Types of Scour

Because scour equations are type-specific, the first step in determining the potential depth of scour is to identify the types of scour that occur at the project site. For instance, an equation for calculating local scour will give an incorrect depth if applied to a site affected only by constriction scour. Five types of scour are defined in Chapter 2. They include bend scour, local scour, constriction scour, drop/weir scour and jet scour.

All of the scour equations presented are empirical. Empirical equations are based on repetitious experiments or measurements in the field and, therefore, can be biased toward a specific type of stream from which the measurements were made. In general, however, empirical equations are developed with the intention to error on the conservative side if applied correctly.

The scour equations may distinguish between live-bed and clear-water conditions. These categories refer to the sediment loading during the design event. Live-bed conditions exist when stream flow is transporting sediment at or near its capacity. Under such conditions, erosion is offset by deposition, as stream flow needs to "drop" sediment in order to "pick up" new sediment. Clear-water conditions exist when stream flow is transporting sediment at a rate that is far below its capacity. Such conditions often occur downstream of dams. Because clear-water stream flow is "sediment-starved," it has the capacity to entrain and transport sediment without associated deposition. Accordingly, clear-water conditions usually produce deeper scour depths than live-bed conditions.

Local Scour

Research on scour has focused on local scour at bridge piers and abutments. If the geometry of an obstruction, such as a boulder or rootwad, can be equated to the geometry of a pier, then pier-scour equations are applicable. If the location and shape of the obstruction more closely resembles a bridge abutment rather than a pier, then scour equations for bridge abutments should be used. Obstructions that resemble bridge abutments include woody-debris installations or similar structures that are attached directly to the streambank. Equations for estimating pier and abutment scour are presented below.

Estimating Pier Scour

Numerous equations are available for predicting scour depths near piers. In general, these equations have been developed for sand-bed rivers. However, when applied to streams with larger-size bed material (i.e., gravel-bed streams), these equations will tend to give conservative results. As determined by these equations, the scour depths for gravel-bed streams may not occur to the extent predicted, or they may take quite a long time to occur. The pier-scour equation presented below includes an adjustment for bed materials that have a D_{50} of six cm or larger (D_{50} refers to the median grain size of bed material and must be expressed in millimeters) and thus is applicable to gravel-bed streams. Expert judgment should be used to adjust the calculated value, if needed, based on observed stream conditions. In addition, the results of Equation 18 (in this appendix) can be used to evaluate the results of the pier scour analysis.

When using a pier-scour equation to estimate scour near an obstruction, the obstruction must be represented as a pier. For instance, a boulder may be represented in the equation by a cylindrical pier of equal diameter. A log or rootwad may be represented as a round or square-nosed pier of the appropriate length. Note that the pier-scour equations assume that the pier extends above the water surface. When pier-scour depth is calculated for obstructions that do not extend through the water surface (under the analyzed flow), the resulting scour depth should be reduced slightly, according to the judgment of the design engineer.

One of the more commonly applied and referenced pier-scour equations is the Colorado State University Equation.[3] While the equation does not differentiate between live-bed and clear-water scour, it can be applied under both conditions.[3] In addition, the equation includes a correction factor (K_4) to adjust for bed materials of D_{50} greater than or equal to six cm.

The U. S. Department of Transportation recommends using two times the scour depth as a reasonable estimate of scour-hole top width in cohesionless materials such as sands and gravels.[3] Scour-hole top width is measured from the edge of the pier to the outside edge of the adjacent scour hole.

Colorado State University Equation for piers

$$d / y_1 = 2.0\, K_1 K_2 K_3 K_4 (b/y_1)^{0.65} Fr^{0.43}$$ (EQUATION 6)

Where: d = maximum depth of scour below local streambed elevation (m)
y_1 = flow depth directly upstream of the pier (m)
b = pier width (m)
Fr = Froude number: $V / (g\,y)^{0.5}$ (dimensionless)
where: V = velocity of flow approaching the abutment (m/s)
g = acceleration due to gravity (9.81m/s^2)
y = flow depth at pier (m)

For the special case of round-nosed piers aligned with the flow, then:
For $Fr \leq 0.8$, $d \leq 2.4$ times the pier width
For $Fr > 0.8$, $d \leq 3.0$ times the pier width

K_1 = correction factor for pier nose shape:
For approach flow angle of attack > 5 degrees, $K_1 = 1.0$
For approach flow angle of attack ≤ 5 degrees:

square nose	$K_1 = 1.1$
round nose	$K_1 = 1.0$
circular cylinder	$K_1 = 1.0$
group of cylinders	$K_1 = 1.0$
sharp nose	$K_1 = 0.9$

K_2 = correction factor for angle of attack of flow from Table E-3
$K_2 = (\cos\theta + L/b \sin\theta)^{0.65}$

Where: L = length of the pier (along the flow line which is being directly subjected to impinging flow at the angle of attack (m)
b = pier width (m)
θ = flow angle of attack to pier (in degrees)

K_3 = correction factor for bed conditions, based on dune height, where dunes are repeating hills formed from moving sand across the channel bed. For gravel-bed rivers, the recomended value of K_3 is 1.1.

θ	L/b = 4	L/b = 8	L/b = 12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.8	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

*Table E-3. K_2 based on L/b and **θ** .*

Bed Conditions	Dune Height (m)	K_3
clear-water scour	N/A	1.1
plane bed and anti-dune flow	N/A	1.1
small dunes	0.6 to 3	1.1
medium dunes	3 to 9	1.1 to 1.2
large dunes	≥ 9	1.3

Table E-4. K_3 based on bed conditions and dune height.

K_4 = *correction factor for armoring of bed material (scour decreases with armoring)*

K_4 *range* = 0.7 *to* 1.0
$K_4 = 1.0$, *for* $D_{50} < 0.06$ m, *or for* $V_r > 1.0$
$K_4 = [1 - 0.89 (1-V_r)^2]^{0.5}$, *for* $D_{50} \geq 0.06$ m,

where:
$V_r = (V - V_i)/(V_{c90} - V_i)$
$V_i = 0.645 (D_{50}/b)^{0.053} V_{c50}$
$V_c = 6.19 \, y_1^{1/6} D_c^{1/3}$

and:
V = *approach flow velocity (m/s)*
V_r = *velocity ratio*
V_i = *approach velocity when particles at a pier begin to move (m/s)*
V_{c90} = *critical velocity for* D_{90} *bed material size (m/s)*
V_{c50} = *critical velocity for* D_{50} *bed material size (m/s)*
g = *acceleration due to gravity (9.81 m/s²)*
D_c = *critical particle size for the critical velocity,* V_c *(m)*
y_1 = *flow depth directly upstream of the pier (m)*

Estimating Scour at Abutments

Like pier-scour equations, abutment-scour equations have generally been developed for sand-bed rivers. When applied to streams with larger-size bed material (i.e., gravel-bed streams), these equations will tend to give conservative results. The scour depths predicted by these equations may not occur or may take quite a long time to occur on gravel-bed streams. "Reliable knowledge of how to predict the decrease in scour-hole depth when there are large particles in the bed material is lacking."[4]

Nonetheless, the equations that are available work for sand-bed rivers, and their results yield a conservative estimate, over-predicting the scour depth on gravel-bed streams. As always, judgment should be used to adjust the calculated value, as needed, based on observed stream conditions. On coarse-grained streams, this will usually mean reducing the calculated value. The results of Equation 18 in this appendix can be used to evaluate the results of the abutment scour analysis.

The Froehlich Equation presented below can be used to estimate scour at an abutment or abutment-like structure.[3] Several variables are included in the equation to describe parameters, such as the abutment shape, angle with respect to flow and abutment length normal to the flow direction. When using this equation to calculate scour for a structure such as a log jam, these parameters should be coupled with expert judgment to describe the structure as best as possible. Note that the abutment-scour equation assumes that the abutment extends above the water surface. When abutment scour depth is calculated for obstructions that do not extend through the water surface (under the analyzed flow), the resulting scour depth should be reduced slightly, according to the judgment of the design engineer.

Froehlich Equation for Live-Bed Scour at Abutments

$$d / y = 2.27 K_1 K_2 (L' / y)^{0.43} Fr^{0.61} + 1.0 \qquad \text{(EQUATION 7)}$$

Where: **d** = *maximum depth of scour below local streambed elevation (m)*
y = *flow depth at abutment (m)*
K_1 = *correction factor for abutment shape where:*
vertical abutment = 1.0
vertical abutment with wing walls = 0.82
spills through abutment = 0.55
K_2 = *correction factor for angle of embankment to flow =* $(\theta / 90)^{0.13}$

where: **θ** = *angle between channel bank and abutment*
θ *is > 90 degrees if embankment points upstream*
θ *is < 90 degrees if embankment points downstream*

L' = *length of abutment projected normal to flow (m)*
L' = A / y A = *flow area of approach cross section obstructed by the embankment* (m^2)
Fr = *Froude number of flow upstream of thhe abutment* = $V / (g\, y)^{0.5}$
where: **V** = *velocity of flow approaching the abutment (m/s)*
g = *acceleration due to gravity* ($9.81\ m/s^2$)
1.0 is added as a safety factor.

Clear-Water Scour at an Abutment

U. S. Department of Transportation recommends using the live-bed scour equation presented above to calculate clear-water scour at an abutment.[3]

Bend Scour

Scour occurs on the outside of channel bends due to spiraling flow, as described in Chapter 2. Bend scour removes materials from the bank toe, precipitating toe erosion or mass failure.

Field observation/measurement of scour at established bends can yield a quick indication of the magnitude of scour expected if correlated to the flows that produced the scour. A first estimate can also be obtained by assuming the scour in any given bend to be about equal to the flow depth found immediately upstream and downstream of the bend.[5] This estimate will be somewhat conservative for mild bends.

G. J. Hoffmans and H. J. Verheij presented the following equation, developed by C. R. Thorne,[6] based on flume and large-river experiments where the mean bed-particle size varied from 0.3 to 63 mm. This equation is applicable to gravel-bed streams.

Thorne Equation

$$d / y_1 = 1.07 - \log(R_c/W - 2) \quad \text{for } 2 < R_c/W < 22 \qquad \text{(EQUATION 8)}$$

Where: **d** = *maximum depth of scour below local stream bed elevation*
y_1 = *average flow depth directly upstream of the bend*
W = *width of flow*
R_c = *radius of curvature at channel centerline*

The width of flow in Equation 8 corresponds to the width of active flow. This width is subject to engineering judgement. However, it often corresponds to the bankfull top width for streams that are flowing near or above bankfull stage. English or metric units may be used.

S. Maynord reviewed bend scour estimates for natural, sand-bed channels and presented one bend-scour equation by W. Wattanabe and a second method of his own.[7] These two equations are listed below. They are useful for predicting scour depths on sand-bed streams and for determining conservative scour depths (for comparison to other methods) on streams with coarser bed materials.

Maynord Equation

$$D_{mb}/D_u = 1.8 - 0.051\ (R_c/W) + 0.0084\ (W/D_u) \qquad \text{(EQUATION 9)}$$

Where: **D_{mb}** = *maximum water depth in bend*
D_u = *mean channel depth at upstream crossing (cross-sectional area/W)*
R_c = *radius of curvature at channel centerline*
W = *width of flow at upstream end of bend*

Notes:

- *Equation 9 was developed from measured data on 215 sand-bed channels.*
- *The data were biased for flow events of one- to five-year return intervals.*
- *Equation does not apply when higher return intervals occur that cause overbank flow exceeding 20 percent of channel depth.*
- *There is no safety factor incorporated into this equation; this is the mean scour depth based on the sites measured.*
- *A safety factor of 1.08 is recommended.*
- *The equation is limited to: $1.5 > R_c/W > 10$ (use $R_c/W = 1.5$ when < 1.5), and limited to: $20 > W/D_u > 125$ (use $W/D_u = 20$ when < 20).*
- *English or metric units may be used.*
- *The width of flow in Equation 9 corresponds to the width of active flow. This width is subject to engineering judgement. However, it often corresponds to the bankfull top width for streams that are flowing near or above bankfull stage.*

Wattanabe Equation

$$d_s/D = \alpha + \beta(W/R_c) \qquad \text{(EQUATION 10)}$$

Where: $\alpha = 0.361\ X^2 - 0.0224X - 0.0394$

$X = \log_{10}(WS^{0.2}/D)$

S = bed slope

d_s = scour depth below maximum depth in unprotected bank

W = channel top width (water surface width)

D = mean channel depth (cross-sectional area/W)

$\beta = 2/(\pi\ 1.226\ ((1/\sqrt{f}\ ) - 1.584)\ x\ )$

f = Darcy friction factor = 64/Re where Re = Reynolds number

$x = 1/\ [1.5\ \ f\ \{(1.11/\sqrt{f}\ ) - 1.42\}\ \sin\sigma + \cos\sigma\ ]$

$\sigma = \tan^{-1}\ [\ 1.5\ \ f\ ((1.11/\sqrt{f}\ ) - 1.42)] = f$

Notes:

- *Results correlate well with Mississippi River data and predicted Thorne and Abt data (1993) by about 25 percent.*
- *Limits of application are unknown.*
- *A safety factor of 1.2 is recommended with this method.*
- *English or metric units may be used.*

Constriction Scour

Constriction-scour equations were developed primarily from flume tests with the constriction resulting from bridge abutments. However, these equations apply equally well to natural constrictions or constrictions caused by installation of instream structures such as groins.

The following constriction equations are based on either live-bed or clear-water conditions. Live-bed conditions occur when the bed material upstream of the constriction is in motion. Clear-water conditions occur when the bed material is not in motion.

Live-Bed Conditions

The following equation for live-bed constriction scour was developed primarily for sand-bed streams. Its application to gravel-bed streams is useful in two ways:

1. it provides a conservative estimate of scour depth; and
2. it can, by extrapolation of the data in *Figure E-4,* provide scour-depth estimates for streams with gravel-sized bed materials.

Coarse sediments in the bed may limit live-bed scour. When coarse sediments are present, it is recommended that scour depths under live-bed and clear-water conditions (see next section) be calculated and that the smaller of the two calculated scour depths be used. As always, expert judgment should be used to adjust the calculated value as needed, based on experience and observed stream conditions. On coarse-grained streams, this will usually mean reducing the calculated value.

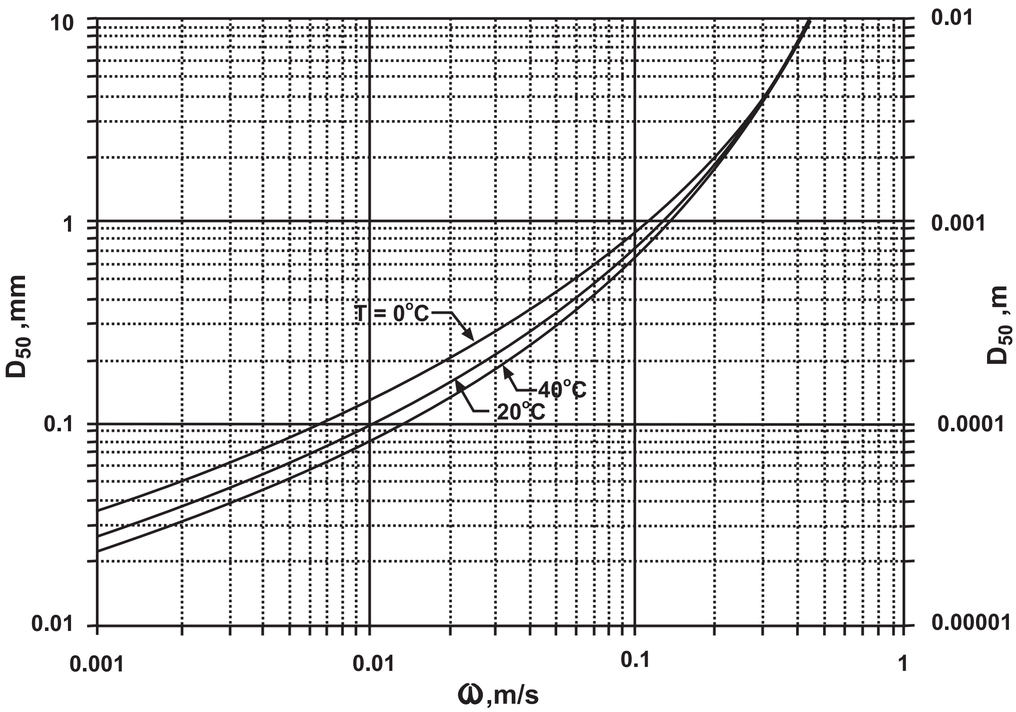

Figure E-4. Fall velocity of sand-sized particles.

Laursen Equation for Live-Bed Conditions[3]

$$y_2 / y_1 = (Q_2/Q_1)^{0.86} (W_1/W_2)^A \quad d = y_2 - y_0 \qquad \text{(EQUATION 11)}$$

Where:
- d = average depth of constriction scour (m)
- y_0 = average depth of flow in constricted reach without scour (m)
- y_1 = average depth of flow in upstream main channel (m)
- y_2 = average depth of flow in constricted reach after scour (m)
- Q_2 = flow in constricted channel section (m^3/s)
- Q_1 = flow (m^3/s) in upstream main channel (disregard floodplain flow)
- W_1 = channel bottom width at upstream cross section (m)
- W_2 = channel bottom width in constricted reach (m)
- A = exponent from Table E-5
  - where: ω = fall velocity (m/s) of bed material based on D_{50} (see Figure E-4)
  - U_* = shear velocity = $(gy_1S_e)^{0.5}$ (m/s)
    - where: g = acceleration due to gravity (9.81 m/s^2)
    - S_e = slope of energy grade line in main channel

Note:

This equation assumes that all stream flow passes through the constricted reach. In review, coarse sediments in the bed may limit live-bed scour. When coarse sediments are present, it is recommended that scour depths under both live-bed and clear-water conditions (see following equation) be calculated scour depths be used.

U_* / ω	A	Mode of Bed Material Transport
< 0.5	0.59	Mostly bed load
0.5 to 2.0	0.64	Mostly suspended load
> 2.0	0.69	Mostly suspended load

Table E-5. Exponent "A" based on U_* / ω.

Clear-Water Conditions

The following equation calculates constriction scour under clear-water conditions. Unlike the live-bed equation presented above, this equation makes allowance for coarse bed materials.

Laursen Equation for Clear-Water Conditions[3]

$$y_2 = \{0.025\ Q_2^{\,2}/[D_m^{\,0.67}\, W_2^{\,2}]\}^{0.43},\ d = y_2 - y_0 \qquad \text{(EQUATION 12)}$$

Where: d = average depth of constriction scour (m)

y_0 = average depth of flow in constricted reach without scour (m)

y_2 = average depth of flow in constricted reach after scour (m)

Q_2 = flow in constricted channel section (m^3/s)

$D_m = 1.25D_{50}$ = assumed diameter of smallest nontransportable particle in the bed material in the constricted reach (m)

W_2 = channel bottom width in constricted reach (m)

Drop/Weir Scour

Two equations are presented here for estimating scour depths for flow pouring over a vertical drop structure. *Figure E-5* shows the typical configuration of such structures. The equations were developed to estimate scour immediately downstream of vertical drop structures and sloping sills.

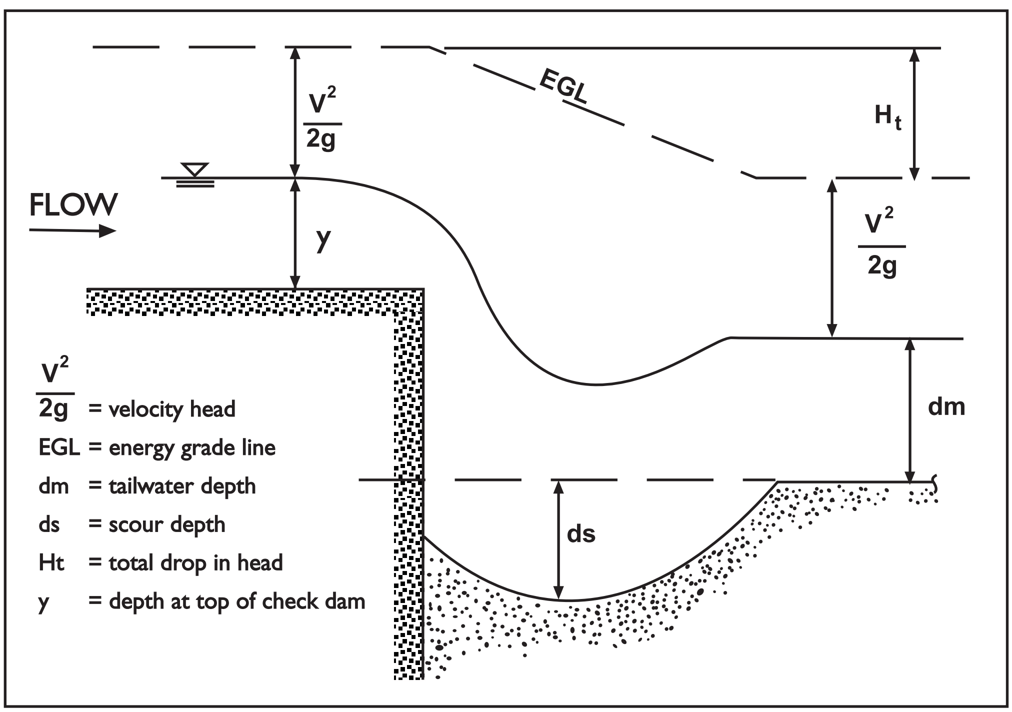

Figure E-5. Schematic of a vertical drop caused by a drop structure.

True vertical drop structures typically include weirs and check dams constructed of materials able to maintain sharp, well-defined crests over which stream flow spills. Drop structure and weirs constructed of logs and tightly constructed rock can create hydraulic conditions associated with vertical drop structures. Structures constructed of loose rock usually form a sloping sill.

Equation 13 is recommended for predicting scour depth immediately downstream of a vertical drop structure and for determining a conservative estimate of scour depth for sloping sills.[8] Equation 14 specifically addresses sloping sills constructed of rock. When designing check dams, weirs, grade controls and similar structures, it is recommended that the designer use these equations as needed (using professional judgment) to estimate expected scour depth immediately downstream of the structure.

U.S. Bureau of Reclamation Equation - Vertical Drop Structure[8]

$$d_s = KH_t^{0.225}q^{0.54} - d_m \qquad \text{(EQUATION 13)}$$

Where: d_s = *local scour depth (below unscoured bed level) immediately downstream of vertical drop (m)*
q = *discharge per unit width ($m^3/s/m$)*
H_t = *total drop in head, measured from the upstream to downstream energy grade line (m)*
d_m = *tailwater depth immediately downstream of scour hole (m)*
K = *1.9 dimensionless*

The depth of scour calculated in Equation 13 is independent of bed-material grain size. If the bed contains large or resistant materials, it may take years or decades for scour to reach the depth calculated in Equation 13.

Laursen and Flick Equation - Sloping Sill[9]

$$d_s = \{ [4 (y_c/D_{50})^{0.2} - 3 (R_{50}/y_c)^{0.1}] y_c \} - d_m \qquad \text{(EQUATION 14)}$$

Where: d_s = *local scour depth (below unscoured bed level) immediately downstream of vertical drop (m or ft)*
y_c = *critical depth of flow (m or ft)*
D_{50} = *median grain size of material being scoured (m or ft)*
R_{50} = *median grain size of stone that makes up the grade control, weir or check dam (m or ft)*
d_m = *tailwater depth immediately downstream of scour hole (m or ft)*

Jet Scour

Although jet scour is a phenomenon associated with streams, it is not typically a component of streambank or instream structure design. In special cases where jet scour may be desirable (or unavoidable) and analysis is necessary, the designer should consult a hydraulic design manual such as Simons & Senturck[10] for guidance.

Check Method - U.S. Bureau of Reclamation Method

A method developed by the Bureau of Reclamation provides a multipurpose approach for estimating depths of scour due to bends, piers, grade-control structures and vertical rock banks or walls.[11] The method is usually not as conservative and possibly not as accurate as the individual methods presented above.

The Bureau of Reclamation method computes an "average" scour depth by applying a systematic adjustment (**STEP 2** on page E-23) to the results of three regime equations: the Neil Equation, a modified Lacey Equation and the Blench equation (**STEP 1** below).[11]

STEP 1

Neil Equation

Obtain field measurements on an incised reach of the river (i.e., a reach that does not flow overbank except at very high discharge) from which bankfull discharge and hydraulics can be calculated.

$$y_n = y_{bf}(q_d / q_{bf})^m \qquad \text{(EQUATION 15)}$$

Where: y_n = *scoured depth below design-flow level which is adjusted in Step 2 to yield predicted scour depths*
y_{bf} = *average bankfull flow depth*
q_d = *design-flow discharge per unit width*
q_{bf} = *bankfull flow discharge per unit width*
m = *exponent varying from 0.67 for sand to 0.85 for coarse gravel*

Note: Units can be metric or English

Modified Lacey Equation

The Lacey equation was modified with the Blench method of zero bed-sediment transport. An incised reach is not required for this application. With one noted exception, units can be metric or English.

$y_L = 0.47\ (Q/\ f)^{.33}$ (EQUATION 16)

Where: y_L = *mean depth at design discharge*
Q = *design discharge*
f = *Lacey's silt factor = 1.76* $D_{50}^{0.5}$
where: D_{50} = *median grain size of bed material (must be in mm)*

Blench Equation

For zero bed sediment transport factor (clear-water scour):

$y_B = q_d^{0.67}\ /\ F_{bo}^{0.33}$ (EQUATION 17)

Where: y_B = *depth for zero bed-sediment transport*
q_d = *design flow discharge per unit width*
F_{bo} = *Blench's zero bed factor, from Figure E-6*

Note: Units can be metric or English.

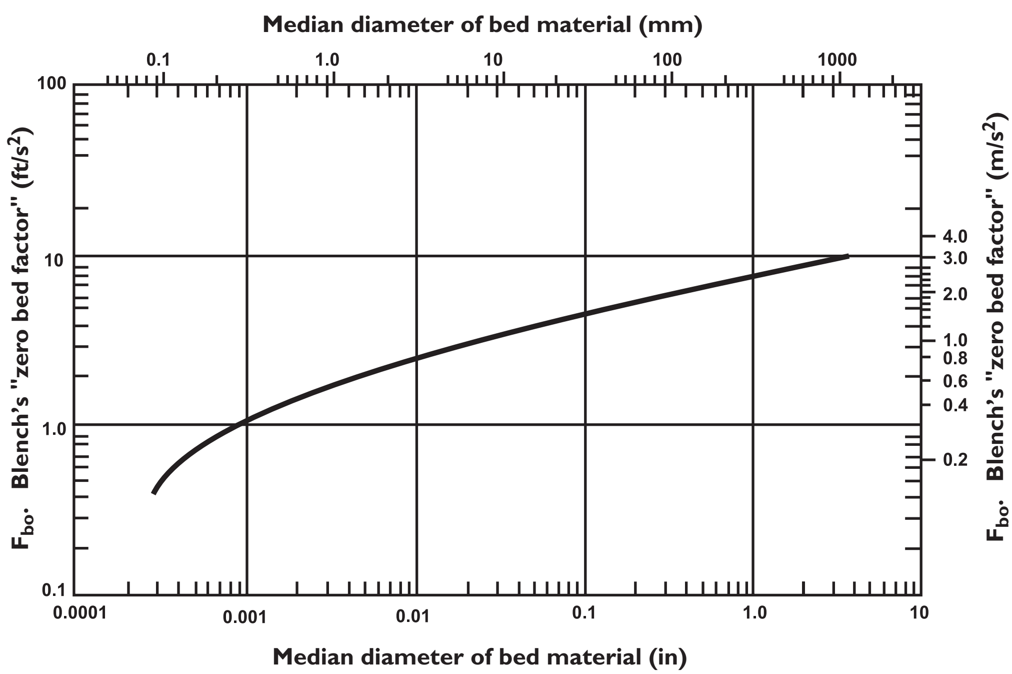

Figure E-6. Chart for estimating F_{bo}*.*

STEP 2

Adjustments to Neil, Modified Lacey and Blench results:

$$d_N = K_N y_N \qquad \text{(EQUATION 18)}$$
$$d_L = K_L y_L$$
$$d_B = K_B y_B$$

Where: d_N, d_L, d_B = *depth of scour from Neil, Modified Lacey and Blench equations, respectively*

K_N, K_L, K_B = *adjustment coefficients for Neil, Modified Lacey and Blench equations as shown in Table E-6.*

Condition	Neil - K_N	Lacey - K_L	Blench - K_B
Bend Scour			
Straight reach (wandering thalweg)	0.50	0.25	0.60
Moderate bend	0.60	0.50	0.60
Severe bend	0.70	0.75	0.60
Right-angle bend	-	1.00	-
Vertical rock bank or wall	-	1.25	-
Nose of piers	1.00	-	0.50 to 1.00
Small dam or grade control across river	0.40 to 0.70	1.50	0.75 to 1.25

Table E-6. Adjustment coefficients based on channel conditions.

REFERENCES

1 Lane, E.W. 1955. Design of stable channels. Transactions of the American Society of Civil Engineers. 120: 1234-1260.

2 U. S. Department of Transportation, Federal Highway Administration. 1988. Design of Roadside Channels with Flexible Linings. Hydraulic Engineering Circular No. 15. Publication No. FHWA-IP-87-7.

3 Richardson, E.V. and S. R. Davis. U.S. Department of Transportation, Federal Highway Administration. 1995. Evaluating Scour at Bridges, Hydraulic Engineering Circular No. 18. Publication No. FHWA-IP-90-017, Third Edition.

4 U. S. Department of Transportation, Federal Highway Administration. 1990. Highways in the River Environment.

5 Hoffmans, G. J. and H. J. Verheij. 1997. Scour Manual. A. A. Balkema Publishers, Brookfield, VT.

6 Thorne, C. R., R. D. Hey and M. D. Newson. 1997. Applied Fluvial Geomorphology for River Engineering and Management. John Wiley and Sons, Inc., New York, NY.

7 Maynord, S. 1996. Toe scour estimation in stabilzed bendways. Journal of Hydraulic Engineering, American Society of Civil Engineers, Vol. 122, No. 8.

8 U. S. Department of Transportation, Federal Highway Administration. 1995a. Stream Stability at Highway Structures. Hydraulic Engineering Circular No. 20.

9 Laursen, E. M. and M. W. Flick. 1983. Final Report, Predicting Scour at Bridges: Questions Not Fully Answered - Scour at Sill Structures, Report ATTI-83-6, Arizona Department of Transportation.

10 Simons, D. B. and F. Senturk. 1992. Sediment Transport Technology. Water Resources Publications, Littleton, CO.

11 Bureau of Reclamation, Sedimentation and River Hydraulics Section. 1984. Computing Degradation and Local Scour, Technical Guideline for Bureau of Reclamation, Denver, CO.

APPENDIX F >>>
<<< APP. TABLE OF CONTENTS
<<< TABLE OF CONTENTS